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OVERVIEW OF NASA'S ADAPTIVE STRUCTURES PROGRAM

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Abstract

The paper reviews the National Aeronautical and Space Administration's (NASA) research program, flight experiments and flight application related to Adaptive Structures. Emphasis is on results from both experimental and flight hardware test programs that helps validates its theoretical performance. The paper includes the role of Adaptive Structures to meet NASA's current and future technology and programmatic needs.

Introduction

NASA's research program in Adaptive Structures was initiated about six (6) years ago to provide technologies for large (20-50 meters in dimension) precision (submicron) space structures for observations and for attenuation of noise in enclosed systems. For large space systems, the current design approach for thermally stable passive structures will not meet the performance and moreover the systems cannot be validated by ground tests(1) . The goal is to meet the stringent requirements while reducing cost and increasing reliability. With more stringent interior noise requirements as the aircraft performance is increased requires aggressive technology in noise reduction while reducing weight and cost . These technologies are potentially applicable to reduction of launch vehicle shroud noise that are significant design requirements on spacecraft subsystems. More recently, significantly more emphases is on smaller, less expensive and shorter development spacecraft. Significant advances toward these objectives can be made by introducing "robustness" into the design, rather than to impose stringent controls on design, analyses, fabrication, and testing, to reduce overall cost while increasing

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Introducing Adaptive Structures into the structural design increases the robustness of the structures. One definition of Adaptive Structures are systems whose geometric and structural characteristics can be beneficially modified during its operational life to meet the mission requirements (4). The design requires the direct integration of actuators, sensors and controllers into the load carrying structure to adapt the structure through remote commands or automatically in response to internal or external stimulations. Providing the designers the capability to introduce adaptability into the previously passive designs resulted in an explosive interests by engineers in universities, industry and government. Two Adaptive Structures conferences (5), two referred journals and many sessions attached to other technical meetings reflects the interest. Significant strides are in progress to transition basic research to applications. Several flight experiments are in development along with one flight application as part of the Wide Field Planetary Camera II to help correct the optics of the Hubble Telescope to be launched within the year. The rapid transition of Adaptive Structures into flight experiments and applications is due to the initial emphases on laboratory demonstration experiments and the infrastructure of realistic NASA funded testbeds at three NASA centers (6) and the Massachusetts Institute of Technology (MIT).

The paper presents NASA's recent progress in Adaptive Structures. As the technology is developed, its applicability to a wide range of applications such as miniature low cost spacecraft is more evident.

Background

The technical challenge that stimulated the initial research in Adaptive Structure was the goal of attenuating and controlling the vibration motion of large flexible space observation structures. Since the large space structure are larger than the dimensions of the shroud and must be assembled or deployed in space; research was concentrated on truss type structures. Typical. of initially proposed approaches was to place a large number of actuators (eg. proof mass) and sensors and control the vibration of the mechanical system using multiple input, multiple output MIMO control systems. Partially as a result of a NASA sponsored Control. Structure Interaction (CSI) program to integrate the results of controls and structures, testbeds were fabricated for various researchers to experimentally validate their state-of-the-art controller designs. The results indicated the need for very accurate models of the structure to attain the desire performance. The accuracy requirements were very stringent and could be obtained at best by large expenditure of funds.

Improvement in the fidelity of actuators and sensors measurements compatible with material strains associated with precision structural motion provided the capability to adapt the structure itself to respond to meet the performance requirements. This lead to the development of active members with actuators imbedded or mounted on the surface of truss members or in-line actuators with actuator material in the load path of the truss structural element. In both cases, the active member functioned as a load transmitting structure as well as an actuator and sensor. For space applications, piezo-electric (7) material provided the displacement fidelity, stiffness, and frequency response for precision structures. The initial research demonstrated the capability to add structural damping at very low displacement levels using locally controlled active members.

Many other issues became equally important before large precision structures are feasible for flight. The issues in a typical possible flight scenario are:

- o Ground validation tests: ground validation tests for large precision structures is very difficult and results in low quality test data at high expense.
- o Deployment reliability: difficulty exists in designing reliable deployable systems.
- o Loose joints: difficulty exists in eliminating and validating by ground tests the presence of loose joints that is a cause "chaotic" non-linear structural response in space.
- o System identification: the structural characteristics must be experimentally determined in space.
- o Static adjustment: precision static alignment in the presence of the space environment, including thermal, for its 10-30 year life.
- o Dynamic adjustment: the dynamic characteristics requires modification to provide the required dynamic controls through damping, isolation and suppression.
- o Reliability: the design must accommodate redundancies.

The incorporation of the concepts of Adaptive Structures into the design of the precision space structures promises to provide partial solutions to all the major issues.

Noise reduction in shell type structures used for aircraft fuselage or shroud was initiated by using piezo-electric actuators mounted to the surface or imbedded in composite materials to add active damping or modify selected high power mode shapes. This technology is potential applicable to reducing the acoustic response levels of the launch vehicle shrouds at potential. detrimental frequencies for the spacecraft. Similarly lateral. vibration motions of rotating systems are attenuated using piezo-electric actuators.

Other spacecraft applications are the use of low bandwidth thermally actuated long stroke actuators for use as a single pin puller. Both Shape Memory Alloy and high output paraffin actuators are candidates. The advantage of these prime movers over pyrotechnic energy sources is the resulting shock levels are substantially reduced; this feature is especially important for miniature spacecraft or subsystems where difficulties exist in establishing physical distance to attenuate the high shock environment from critical electrical components.

Testbeds

The rapid progress to transition basic research to flight programs is attributable to the establishment of various realistic testbeds at various NASA and NASA sponsored organizations. These testbeds were valuable in focusing research and helped develop realistic hardware and electronics necessary to perform the desired functions. Most of the testbeds can accommodate active members by replacing the passive members. Some of the recent NASA testbeds are:

o Figure 1 is the Langley Research Center (LaRC) Controls Structures Interaction (CSI) Phase O Evolutionary Testbed that is a 17m x 7.6m x 3m truss structure with an antenna subsystem to be precisely pointed during its disturbance.

o Figure 2 is the Jet Propulsion Laboratory (JPL) Micro-Precision Interferometer (MRI) with three nearly orthogonal trusses. The dimensions of the three trusses are 7m x 6.3m x 5.5m. The objective is to demonstrate relative position control of selected locations meters apart to about 10 nanometers when subjected to disturbances. Figure 3 is a 3.8 m diameter truss backup structure (Precision Segmented Reflector [PSR]) onto which hexagonal composite panels are mounted to form one optical surface.

o Figure 4 is the Marshall Space Flight Center (MSFC) Controls, Astrophysics, and Structures Experiment in Space (CASES) that is a 32m long deployable/retractable boom with an occulting plate at the end. The objective is to maintain the alignment of the occulting plate relative to detectors at the base of the boom.

o Figure 5 is the MIT Optical Interferometer with six (6) 3.5 m long trusses forming a tetrahedron. The objective is to minimize the relative motion between points at different locations on the tetrahedron when subjected to external disturbances.

Technical Progress

Ground Testing

The limitations of ground test validation technology for large precision structures are not properly appreciated (8) . Unless these limitations are overcome, these structures will never be adopted on future programs since experience shows the necessity of ground tests to validate the flight system. The incorporation of Adaptive Structures relaxes the ground test requirements by several orders of magnitude because the structure is adjustable during its operational life.

Deployment/Assembly

A potential problem with structural deployment or assembly is the accumulation of strain energy within the structure while being positioned in space (9). The magnitude of accumulated strain energy is directly related to external forces for deployment or assembly. When the external force exceeds the design capability, failure occurs. Inclusion of active members capable of relieving strain energy (slowing extends/contracts under tensile/ compressive loads) at the potential locations of strain energy accumulation can assure the external loads for deployment/assembly are safely within the design capability. Thus the requirements for stringent tolerance control of many structural elements is relaxed and robustness in the design is through strain energy control.

Structural Linearization

If gaps exists in the joints after deployment or assembly, the structural response at low levels may be "chaotic" or exhibit other non-linear characteristics. Most high performance control systems requires a predictable structural response. The design is robust when the capability exists to adjust the structure to preload the members or preload the joints using active members. Research and tests are in progress on the PSR testbed.

Static Shape/Position Adjustment

Once the precision structure is in its operational position, its static position must be precisely located. The desired static position can be attained by adjusting active members. The active members for this application include mechanical "screw jack" or inch worm PZT actuators (7) for higher resolution. Slowing varying distortions due to thermal loads can be corrected if the frequency response of the active members are slightly higher. Significant improvements in static accuracy of the PSR structure was achieved using only a limited number of active members (10) . Preliminary studies have been initiated to establish if the change in static shape can be estimated by a limited number of internal displacement measurements (11) .

Graphite epoxy composite hexagonal panels with micron level precision are on the PSR structure to develop the surface. The surface accuracy must be maintained during its operational life of about 30 years while in a temperature range of 300°K to an operational 100"K. PZT strips on the back of the PSR panels successfully corrected long wave length errors attributable to distortions resulting from release of strain energy or thermal distortions (12).

The Wide Field Planetary Camera II (WFPC-II) is to replace the existing WFPC on the Hubble Telescope to correct for its wave front error. Robustness was added to the system by developing an Articulating Fold Mirror (AFM) capable of angular adjustment during its operation (13) . The lack of confidence of the Fold Mirror to maintain its static angular position in the optics train subjected to vibrations, thermal and space environmental affects resulted in the AFM. Electrostrictive actuators are the prime movers of the AFM and the requirement is for a tilt step size of ≈ one arc sec with a tip/tilt range of ± 206 arc sec. The picture of the AFM is shown in Figure 6. The hardware was developed in about a one year period and is scheduled for a 12/93 launch.

On-Orbit System Identification

The Shuttle flight experiment program Middeck O-gravity Dynamics Experiment (MODE) (14) revealed the difficulties in accurately predicting the dynamics of structures in space from analytical and ground tests. Especially at low amplitudes of vibration. Recently, NASA sponsored ground test programs have revealed the requirement for accurate knowledge of the dynamic models for stability and performance from multiple input-multiple output (MIMO) control systems. To relax ground test requirements and to effectively utilize Adaptive Structures, on-orbit system identification is required. Experiments have proven that modal parameters obtained by using various active members as excitation sources are excellent (15) . Also the performance of the active members can be calibrated by system tests using other active members as exciters (16). Active members provide a more realistic force distribution during the modal test since the forces are applied at locations of maximum strain energy or force.

Vibration Suppression

Various passive and active members for vibration suppression at low amplitudes of vibration have been developed. They include special passive dampers and active members with relative displacement sensors and/or load sensors. To satisfy the displacement resolution and the wide frequency bandwidths, the actuator materials are piezo-electric, electrostrictive and magnetostrictive (7). Figure 7 illustrates one of the designs. Magnetrostrictive actuators provide good performance at lower temperatures such as 100”K.

Most of the research has been performed in vibration suppression. Experiments (17) on the tetrahedron truss show the relative merits of different approaches to control the vibration motion between points AB, BC and CA (A,B and C are locations on different truss legs) and are in Figure 8. Experiments (18) shown in Figure 9 show that active and passive members can effectively quiet the motion of the structure between the excitation source and the voice coil at the optical element. Experiments (19) shown in Figure 10 established that by using multilayer controls, namely disturbance isolation, structural quieting using active/passive members, and optical position control, a disturbance rejection factor of 5100 is achievable and the optical pathlength is stabilized to 5 nm. Another experiment on Figure 1 demonstrates the value of strategically placing active members to damp target modes near the global controller cross over frequency to assure overall system stability (20) . The results are shown in Figure 11. Similar results were obtained on a two-dimensional type structure shown in Figure 3. Active damping using active members was achieved using MIMO: success was only achievable when a very accurate knowledge of the structural model is available. Local analog controllers on each active members are very robust and its affectivity is enhanced through matching its impedance with the structure (21) .

The control of vibration on beams and frame-like structures typically requires as many actuators as the number of modes to be controlled. Controlling both extensional and flexural waves on beams using PZT actuators and PVDF sensors prevents the vibrations from propagating beyond the control location or at the location of the PZT actuator (22). A 20db reduction in panel radiated noise was achieved by using 4 PZT actuators on an 18" diameter aluminum plate by reducing the modal amplitudes (23). On a 12 ft. and 5.5 ft diameter composite cylinder, two PZT actuators are on the skin for one test and two PZT actuators are on the web of the ring frame for the other test (24). At a frequency of 172 Hz, both tests resulted in a 12 db noise reduction as shown in Figure 12. Nine PZT actuators mounted on the side of a 12.0 ft aluminum cylinder with a diameter of 5.5 ft using neural network controllers to reconfigure the distribution of forces (25). As shown in Figure 13, use of select actuators to reduce noise while others are to prevent spill over excitation of the shell resulted in a 15.9 db interior noise reduction while attaining a 0.4 reduction in structural response.

Active control of rotor vibration using three PZT actuators demonstrating control of steady and transient vibrations, synchronous and non-synchronous vibrations, relocation of critical speeds and rotor instabilities on ground test has been accomplished (26). Figure 14 illustrates the test setup and partial results. Efforts to develop cryogenic turbopump hybrid magnetic bearing have resulted in a significant damping of 200 lb-see/in that has completely suppressed flexible bending characteristics. While operating in cryogenic temperatures at 14,000 rpm, radial loads of 500 lbs have been produced (27).

Vibration isolation of precision optics on a flexible structure with frequencies above 25 Hz. has been demonstrated to provide a 15 db broadband disturbance rejection over a 300 Hz bandwidth by using a mount designed to be reactionless over 50 Hz. (28). The approach doesn't depend a good model of the flexible structure. A magnetic suspension isolation system has been demonstrated to provide one to two orders of magnitude vibration reduction in the 1-20 Hz frequency range during 20 seconds of mini-gravity environment on an aircraft (29). Research is currently in progress to develop a six degree of freedom isolation system using a Stewart Platform configuration and six magnetostrictive actuators (30). Figure 15 illustrates the overall configuration. The reduction of vibration of cryocoolers has been actively canceled using a multi-axis counterbalance driven by three sets of magnetic actuators. Reduction of two orders of magnitude of the third harmonic was achieved with negligible effect on the other harmonics (31).

To help transition the research into space applications, active damping was successfully demonstrated on a 12 meter truss on a KC-135 aircraft flight (32). Excellent results were achieved with minimal effort on a structure with poor mods 1. characterization. A ground based/ KC-135 flight experiment is planned using an existing flight structure to validate active and passive damping to suppress the jitter of a space laser. A Middeck Active Control Experiment (MACE) is being developed for a Shuttle to be flown in 1994 (33). The objective is to space validate the structures/controls issues related to very flexible structures with multiple payloads, some payloads requiring precise pointing. See Figure 16. Active members are a part of the experiment to provide vibration suppression. Other flight experiments related to interferometer, vibration suppression, space assembly and others are being evaluated.

Other Issues

Other issues being addressed include studies to miniaturize the electronics and power supplies and establish the feasibility of co-locating or even imbedding them into **the composite itself, near** the actuators and sensors. The optimal location of the fewest number of actuators and sensors to achieve the desired structural performance is being studied. The achievement of reliability through redundancies of actuators and sensors exists. The applications appear to limited by the force, stroke, toughness, power, weight and static displacement capabilities of the actuators in the operating space environment. Both new actuators materials and composite actuators combining the active elements with matrix material is being investigated. Also work is continuing to further develop and establish the use of fiber optics as strain sensors when attached or imbedded into structures.

Summary

A very rapid transition of research in Adaptive Structures to applications has occurred in the past five years. The transition can be directly attributable to the emphasis on experimental work that has help re-focus "research" towards those areas that have a near term benefit. Also many flight experiments in Adaptive Structures are being planned that will highlight integration issues with operational spacecraft that are often critical yet overlooked in research programs. Also a realization is that designing robustness into the structural design results in system that meets stringent requirements with a potential savings in cost and schedule. Adaptive Structures provides the "tools" that can increase the robustness of structural design.

This work is directly applicable to many issues related to the recent emphasis on small, quick and inexpensive spacecraft. Also the technology is applicable to many future non-aerospace applications.

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Figures

Figure 1 LaRC Phase O Evolutionary Testbed

Figure 2 JPL Micro Precision Interferometer

Figure 3 Precision Segmented Reflector

Figure 4 MSFC Controls, Astrophysics & Structures Experiment in Space

Figure 5 MIT Optical Interferometer

Figure 6 WFPC-II Articulating Fold Mirror

Figure 7 JPL Active Member

Figure 8 Test Results from the MIT Optical Interferometer

Figure 9 JPL Structural Quieting with Active and Passive Members

Figure 10 JPL Multilayer Control

Figure 11 LaRC/JPL Damping of Modes at Cross Over Frequency

Figure 12 LaRC Noise Reduction in Composite Cylinder

Figure 13 LaRC Noise Reduction, Neural Controllers

Figure 14 LeRC Active Control of Rotor Vibration

Figure 15 Stewart Platform, Six DOF Isolation System

Figure 16 MIT Middeck Active Control Experiment